A Toolbox of Simulators for Groundwater/Surface Water Interaction

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Abstract

To fulfill its extensive responsibilities for environmental quality management, the Corps of Engineers must be able to assess current conditions, identify problem sources, predict constituent migration, foresee future concerns, and design environmental restoration plans. The Corps relies heavily on numerical models of fluid flow and sediment/contaminant transport in surface water and in groundwater to identify the important processes and explore alternatives. Historically, a divide has existed between the surface water and groundwater modelers; each group treating the other's domain as merely sources and sinks. Such simplified division is not always possible. Studies commonly require more intimate knowledge of the exchange of water and contaminants between surface and subsurface hydrologic systems. The ERDC, in collaboration with its university partners, is currently developing, testing, and applying a suite of multidimensional models to simulate groundwater and surface water interactions. As with most simulations, data availability, time and space scales, level of certainty required in the solution dictate the level of model to be applied. As these hydrologic models mature they are incorporated into the US Department of Defense xMS modeling systems. This paper describes the status and direction of these model developments and discusses their appropriate application.

Introduction

Surface water modelers have often ignored the contribution of groundwater to surface water or have treated groundwater as simply a source or sink term. Likewise, groundwater modelers have often treated complex surface water hydrology as merely a constant, or seasonally-varying recharge or evaporation rate. The need to simulate the systems in which groundwater and surface water are closely coupled has forced the two communities to come together to develop integrated numerical models. These models simulate the interaction between surface and groundwater, providing a more complete picture of the overall water balance.

Physical conditions, data availability, and modeling goals may vary greatly. Modelers need a variety of approaches, or tools, from which to choose. This is true of surface water hydrology, groundwater hydrology, and integrated surface water, groundwater hydrologic studies. The most efficient model for simulating infiltration excess runoff may not be capable of tracking the infiltration through the unsaturated zone or saturated flow through a complex subsurface. Conversely, application of a three dimensional (3-D), variably saturated, finite-element model to calculate baseflow in a stream incised in a relatively homogeneous sand may be overly expensive to set up and run, and may provide no better predictions than a much simpler approach. A combination of in-house staff and university partners has collaborated in the development of a toolbox of state-of-the-practice numerical simulators for interacting surface and subsurface hydrologic systems. Selection of the appropriate tool for a given study is based on the strengths and weaknesses of each tool and the dominant physical processes.

The Department of Defense's (DoD's) Groundwater Modeling System (GMS) (Jones, 2001) and Watershed Modeling System (WMS) (Nelson, 2001) are designed specifically for the purpose of providing multi-dimensional support for constructing and evaluating structured and unstructured numerical domains within a common user environment. The numerical toolbox simulators are d to be used within GMS/WMS. This interwoven development of numerical models and model interfaces permits comparison among different approaches and helps choose the best simulator for the particular study.

Modeling Philosophy

Numerical modeling of the hydrology of natural systems requires the simplification of complex phenomena and interactions. The degree of simplification determines the applicability of the modeling approach. The basic philosophy is that all hydrologic systems are controlled by processes that can be simulated at some scale. Any given watershed will have dominant features and processes that must be included in the model simulation to accurately reflect the watershed response to hydro-meteorological inputs. Once the processes are adequately described, additional complexity usually will not provide significantly superior solutions, but may add difficulty and expense to model construction, calibration, and application.

Modeling Approaches

Hydrologic models come in many flavors ranging from the very simple to the very complex. While simple analytical models and lumped-parameter models serve useful purposes, they are not appropriate for assessing spatial details in watershed flow and contaminant transport, or for evaluating proposed changes to the landscape. This discussion of modeling approaches begins with models that provide temporal and spatial detail in the hydrologic processes. While each code in the numerical model toolbox has various options for simulating the physical processes that occur in surface and subsurface hydrologic systems, some common features are found in all. Each solves a form of the shallow water equations on the land surface and each approximates Richards' (1931) equation for partially saturated flow in the subsurface. The spatially-distributed, groundwater/surface water interaction models in the ERDC toolbox are (1.) GHSSA, (2.) FEMWATER123/WASH123D, and (3.) ADH.

GSSHA. Like its predecessor, CASC2D, GSSHA (Gridded Surface Subsurface Hydrologic Analysis) (Downer, 2002) is a process-based model designed for long-term, large basin simulations of watershed response to hydro-meteorological inputs. The ability to simulate both saturated and unsaturated sub-surface flows allows the GSSHA model to be used in watersheds and regions where infiltration excess runoff is not the dominant streamflow producing mechanism (Downer et al., 2002). Simulated processes include: precipitation distribution, snowfall accumulation and melting, precipitation interception, surface water retention, infiltration, overland runoff, erosion and deposition, channel routing of water, sediments, and conservative contaminants, unsaturated and saturated groundwater flow, stream recharge to groundwater, discharge of groundwater to the surface, and evapo-transpiration.

For each process there may be multiple solution techniques, e.g. infiltration calculations by Green and Ampt's method (Green and Ampt, 1911), or Richards' equation. Calculations in GSSHA are based on finite difference and finite volume techniques. The 1-D vertical, head-based form of Richards' equation is used to model all water movement in the unsaturated zone while the 2-D, lateral, saturated flow equations for unconfined groundwater flow are used to simulate the saturated zone (Downer and Howington, 2001). Both domains are solved using an implicit finite difference approach. Employing a 1-D unsaturated solution permits the use of fine resolution near the soil surface (van Dam and Feddes, 2000; Downer, 2002).

Compared to the models described later, GSSHA is a simple model that solves diffusion-like equations in both the surface and subsurface domains, making GSSHA very robust. The model has been applied to several different types of watersheds, under different conditions (for example, Downer 2002, Downer et al. 2002, Talbot et al. 2002). An example of a GSSHA representation of the of a the Central Creek watershed in northeast Texas is shown in Figure 1.

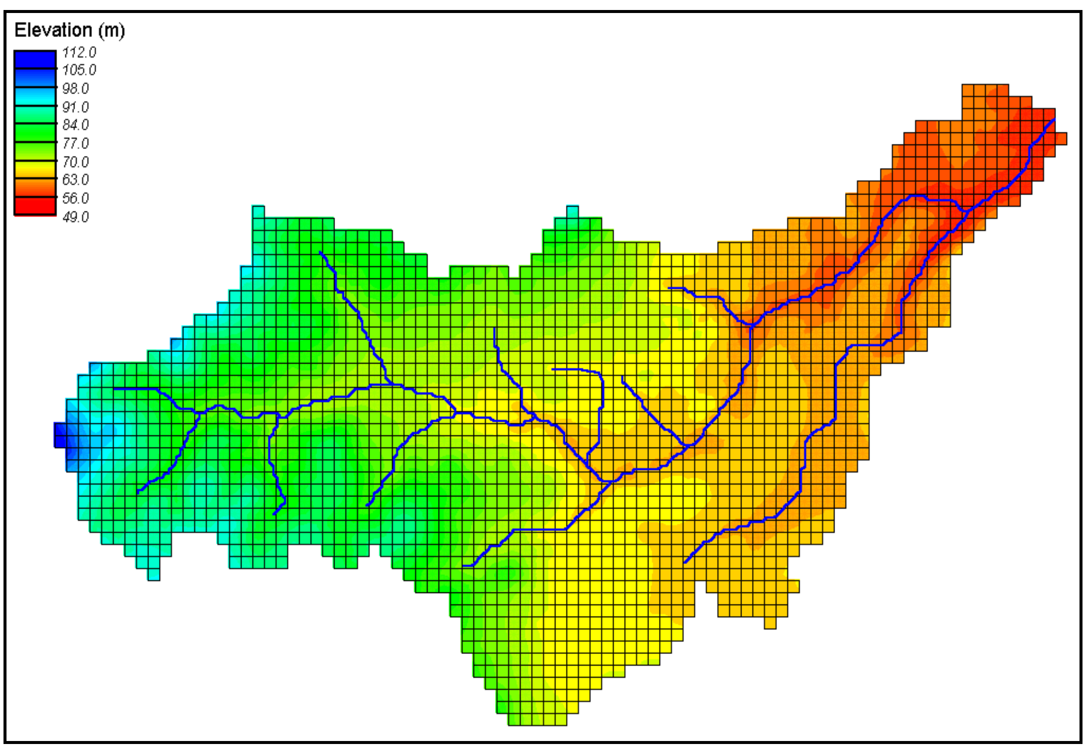

Figure 1. GSSHA representation of 2-D overland flow plane and 1-D channels at Central Creek.

GSSHA runs quickly compared with more computationally-intensive finite element models, and is suitable for use with automated calibration and parameter space searching algorithms, such as GLUE (Beven and Brinley, 1992) or the SCE method (Duan et al., 1992, Senarath et al., 2000).

FEMWATER123/WASH123D. Originally developed for application to the complex 1-D canal, 2-D surface, and 3-D subsurface hydrologic system in South Florida, FEMWATER123 is a time-lagged, sequentially-coupled surface-subsurface interaction code. Maintaining full three-dimensionality in the unsaturated zone permits the simulation of perched aquifers, inter-formation flow (lateral flow in the unsaturated zone), and infiltration processes in heterogeneous systems. Overland flow is simulated with the diffusive wave approximation of the St. Venant equation (Singh, 1996), or if necessary, the full dynamic wave approximation can be used (Yeh et al., 1997). The DoD has used FEMWATER123 to provide simulations of the South Florida system (Figure 2). To accurately simulate the South Florida system, detailed operation procedures for South Dade County (Florida) canal system are built into the 1-D flow module. The operating procedures provide flood protection, clean water supply, and recreational facilities for south Dade County. Given the high degree of interaction among canals, overland and subsurface flows, canal operation procedures must be included to provide operation planners with a viable tool for system-wide simulation and design.

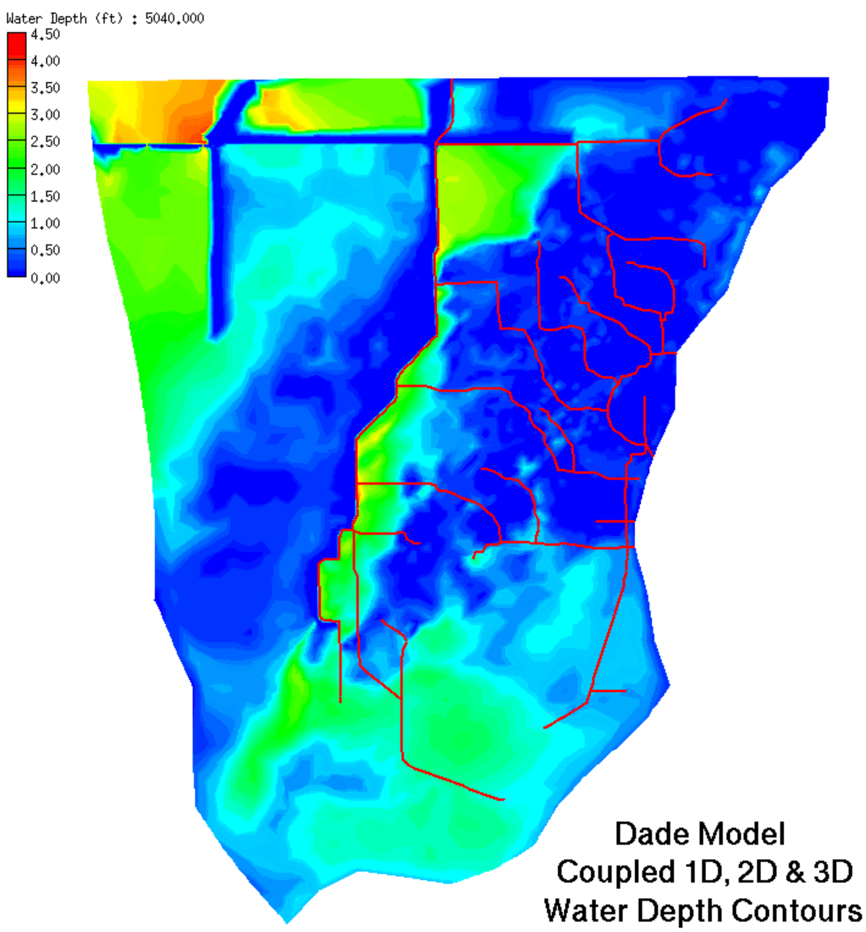

Figure 2. South Dade County (Florida) FEMWATER123 simulation with 1-D canal network.

The domains are discretized using unstructured meshes. The lateral flow capability in the unsaturated zone has proven valuable at other sites, including Pueblo Chemical Depot. At this site, a convex region in the bedrock surface causes the saturated thickness to become very small, and field data cannot be matched if lateral flow in the unsaturated zone is excluded.

WASH123D, based on FEMWATER123, extends the modeling capabilities of the toolbox by including sediment and chemical transport in watershed systems. The model is being applied at the South Fork of the Broad River in the Savannah River Basin. Concerns at the site include excess sediments, nutrients and pesticides. Contaminants originate from overland non-point sources but the stream receives contaminants from both the overland flow plane and from subsurface flows. The WASH123D model was selected for this study because it can track the movement and fate of the chemical constituents in both the surface and subsurface domains. The USEPA has established a system for collecting the data to be used for model calibration and verification. The South Fork of the Broad River watershed, with WASH123D representation of the channel network, is shown in Figure 3.

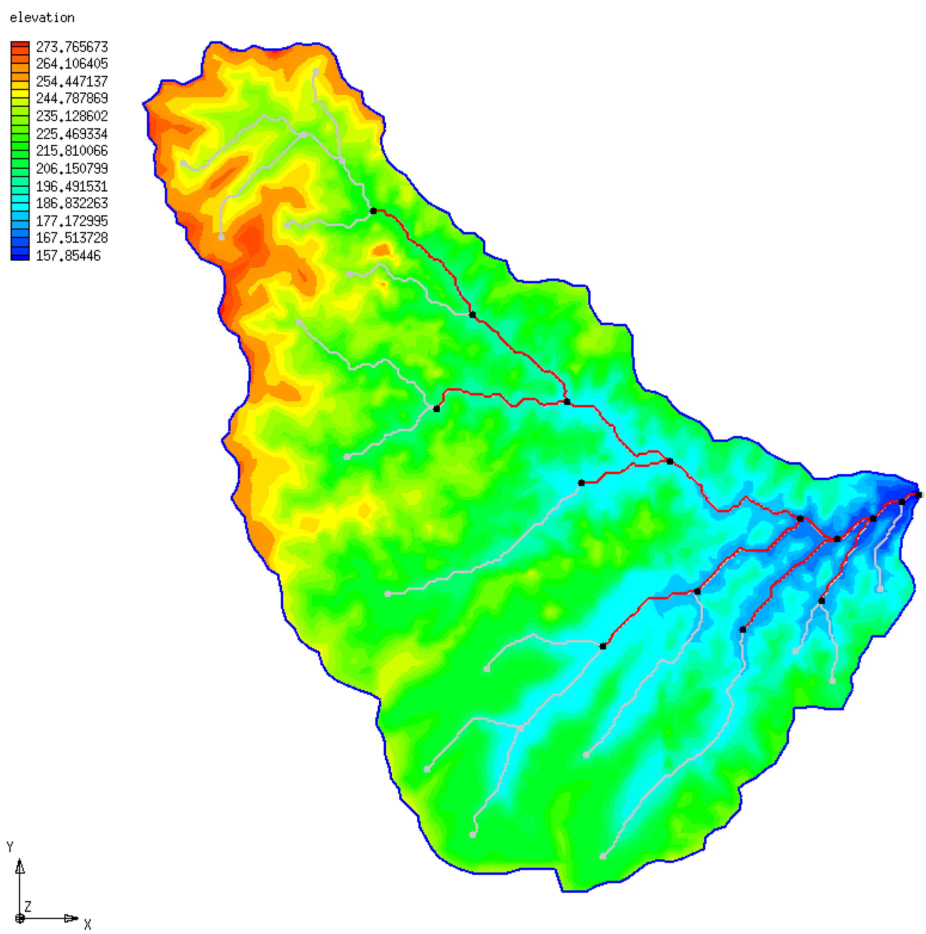

Figure 3. South Fork of the Broad River watershed with WASH123D channel network.

ADH. Like FEMWATER123 and WASH123D, the ADH (ADaptive Hydrology) model (Schmidt and Roig, 1997, Howington et al., 1999) couples 3-D unsaturated subsurface modeling to 2-D shallow water modeling on the ground surface. To ease the computational burden of such a general approach, ADH has been designed from its inception to take advantage of parallel computer architectures where the computational problem is divided into partitions, each solved simultaneously on multiple processors.

Finite elements are used to discretize the domain. Diffusive wave or full St. Venant routing may be simulated on the surface of the 3-D groundwater mesh. The two flow regimes communicate through boundary fluxes computed at the surface of the groundwater system.

Many of the physical problems to be addressed with ADH contain moving steep spatial gradients in the solution variables. Examples include a moving saturation front, intermittent wells in the groundwater system, a traveling wave in the surface water system, or a contamination front in either system. Capturing these phenomena with a fixed-mesh model requires extremely fine mesh resolution throughout the domain. Such resolution is not practical for many problems and is not an efficient use of resources. To avoid these problems, ADH uses local mesh refinement and coarsening (Figure 4). Automatic mesh refinement removes much of the burden from the modeler. The initial mesh must only be fine enough to describe the stratigraphy, define the surface features, and assign boundary conditions. The model will add resolution as needed to complete the simulation. The modeler need not anticipate where steep gradients might appear or what mesh resolution will be appropriate.

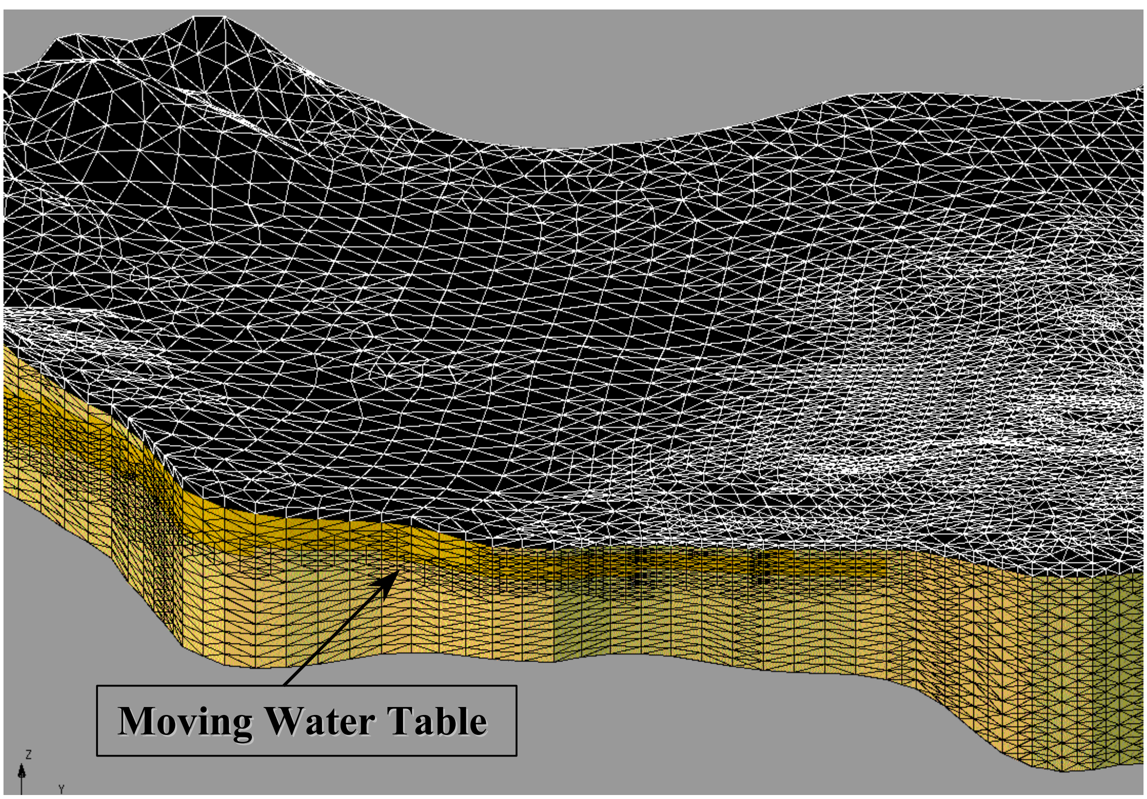

Figure 4. Example ADH mesh at Longhorn Army Ammunition Plant showing local refinement around the moving water table.

Summary

In support of the DoD, Corps of Engineers, and other Federal agencies, the ERDC is actively involved in developing, refining, and applying multiple approaches to surface water/groundwater interaction simulation. Multiple approaches and models are needed to best address a variety of complex problems and situations. Having different approaches contained in a common delivery mechanism encourages experimentation with different models and proper choice of model for the situation.

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Permission has been granted by the Chief of Engineers to publish this information.

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